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Automated Detection and Tracking Systems for Active Sonar

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PREFACE

This document was prepared under NUSC Project No. Q25407, "Automated Detection and Tracking Active Sonar," Princial Investigator, R. F. Dwyer (Code 3314); Program Manager, A. Goodman (Code 33B).

The material in this document was presented at a Code 331 technical meeting. Subsequently, the author received many requests for copies of the viewgraphs used in the presentation. This document is meant to satisfy these requests until a more complete report can be finished.

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There is a significant advantage to detecting signals sequentially. Generally, sequential detection minimizes the average decision time. This is an important requirement in tactial sonar. However, when sequential analysis is coupled with target tracking a powerful automated sequential-detection-tracking system is obtained which can be applied to both active and passive systems. The automated system acts much like a human operator in that it defers a decision until a high level of confidence in the target is reached. On the other hand, target tracks which accumulate low levels of confidence are discarded.

A general discussion of optimum sequential detection of signals to noise from a likelihood ratio formulation is given. These results are applied to active sonar. Specifically, the performance in terms of false alarm probability and false dismissal probability is given for active sonar operating with a limited amount of data. (RH)

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AUTOMATED DETECTION TRACKING SYSTEMS FOR ACTIVE SONAR

INTRODUCTION

The information and viewgraphs in this document were presented at a NUSC/Code 331 technical meeting. A more complete report will be published in the future.

AUTOMATED DETECTION AND TRACKING SYSTEMS FOR ACTIVE SONAR

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N0211-GA-87(L)-00487.8

Viewgraph 1

Automated detection and tracking systems for both active and passive sonar employ sequential decision analysis to detect and track potential targets. The sequential procedure also drops false tracks from memory. This is an important operation in order to maintain finite computer memory limits.

The sequential procedure is a natural way to detect a signal. Consider an operator viewing a display. He will announce a target's presence when he's sure a target is there. This is the basic philosophy behind sequential detection. A target is detected only when there's sufficient cause. But unlike an operator, potential tracks due to noise can be discarded by the sequential procedure.

In this document I will present the fundamentals of sequential detection.

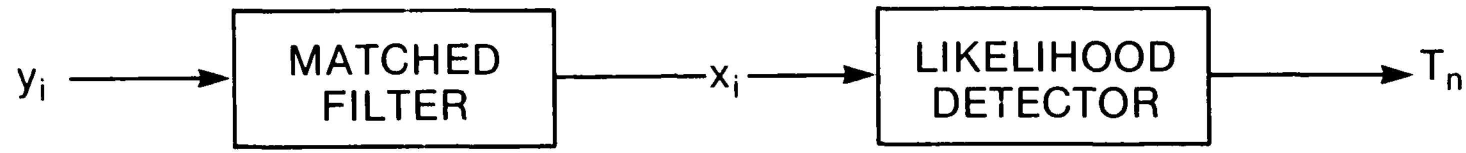
OUTLINE

- INTRODUCTION
- FIXED SAMPLE DETECTION
- SEQUENTIAL DETECTION
- RELATIVE EFFICIENCY
- TRUNCATED TEST (FORCED DECISION)
- GAUSSIAN EXAMPLE
- TWO-DIMENSIONAL GAUSSIAN EXAMPLE
- RAYLEIGH FLUCTUATING TARGET
- CONCLUSIONS

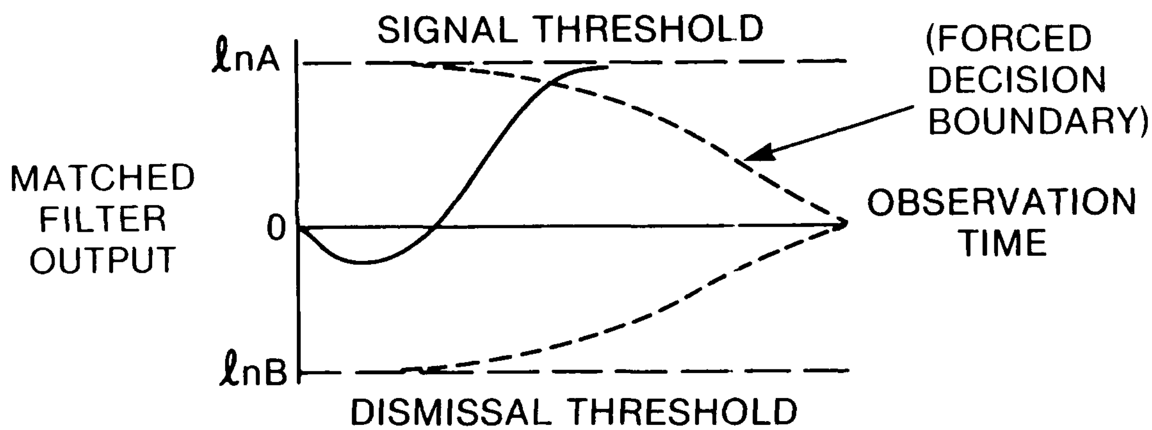
Viewgraph 2

These are the topics that will be discussed in this document. The sequential detector is compared with a fixed sample detector in order to show the sequential detector's optimum property of minimizing the average detection time. The performance measure used is the relative efficiency. A sequential detector with a forced decision boundary is also discussed. These results are important for real tactical situations.

The one-dimensional and two-dimensional Gaussian cases are considered. Then the Rayleigh fluctuating target model of active sonar is discussed in detail.



CW
LFM
CODED PULSE



$B < T_n < A$

$A \sim \dfrac{1-\beta}{\alpha}$

$B \sim \dfrac{\beta}{1-\alpha}$

- SEQUENTIAL DETECTOR - <u>MINIMIZE THE AVERAGE DETECTION TIME</u>
- NEGLECTING EXCESS OVER BOUNDARIES

$$A = \frac{1-\beta}{\alpha} \quad , \quad B = \frac{\beta}{1-\alpha}$$

$$\alpha = \frac{1-B}{A-B} \quad , \quad \beta = \frac{A-1}{A-B}$$

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Viewgraph 3

The sequential detection procedure will be applied at the matched filter output. The active transmission may be CW, LFM, or coded pulses. The likelihood ratio is constructed at the matched filter output to obtain the optimum receiver. Then the sequential analysis procedure is used to detect potential target tracks. Noise tracks are discarded. The advantage of the sequential procedure is that it minimizes the average decision time. This procedure may also be important for long ping durations in surveillance. In this mode a target's presence may be detected before the ping duration is completed giving a tactical advantage to the transmitting ship. However, here I will confine my discussion to multiple transmissions only. This mode is applicable to tactical sonar.

The sequential detection procedure was developed by Abraham Wald. Basically, a decision about the target's presence is deferred until one of two possible boundaries are reached. The loglikelihood ratio output, T_n, for each ping is compared with two thresholds, $\ln A$ and $\ln B$. If $T_n \geq \ln A$, then a target is present. If $T_n \leq \ln B$ noise only is present and the potential track is dropped from memory. Whereas, if $\ln B < T_n < \ln A$, a decision is deferred until the next ping is received. This procedure minimizes the average detection time. However, the amount of data accumulated is now a random variable. In order to prevent long decision times from occasionally occurring a non-constant decision boundary is sometimes employed. This is called a truncated or forced decision test,

because at some time a decision will be forced to occur. Later I will show that if a truncated test is used the decision time can be reduced further, but at the expense of higher error rates. Nevertheless, this may be a reasonable trade-off. The quantification of a forced decision as given later allows an intelligent trade-off to be made.

Wald was able to relate thresholds in terms of false alarm (α) and false dismissal (β) probabilities by neglecting the excess over the boundaries. This means that the sequential detection procedure terminates on the boundary. This is a good assumption for small signal-to-noise ratio problems. But for high signal-to-noise ratio problems more exact methods are needed.

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Operating Characteristics Function (OCF)

$$L(h) = (A^h - 1) / (A^h - B^h)$$

PROBABILITY L(h) OF ACCEPTING H_0 AS A FUNCTION h.

PROBABILITY OF ACCEPTING H_1

$$= 1 - L(h)$$

h SATISFIES THE CONDITION

$$E[e^{T_n h}] = \int_{-\infty}^{\infty} \cdot\cdot \int_{-\infty}^{\infty} T_n^h \; f(\underline{x}; s, s,) \, d\underline{x} = 1$$

$h = h(s, s,)$; SATISFIED AT $h = \pm 1$

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Viewgraph 4

The performance of sequential detection procedures are usually based on the operating characteristic function (OCF) and the average sample number (ASN) as defined by Wald.

The OCF is defined as the probability, L(h), of dismissing the false track as noise (H_0) as a function of the parameter h. Whereas, the probability of accepting the potential track as a target (H_1) is, 1 - L(h). This holds because we assume that the test will eventually terminate.

The parameter h itself is a function of the signal. It can be obtained from the characteristic function from the equation $E[e^{Tnh}] = 1$. This equation will always be satisfied at the points, h = 1, h = -1, and h = 0. However, the objective is to find an analytic expression for h which satisfies the above equation for $-1 \leq h \leq 1$.

Average Sample Number (ASN)

$\ell nB < T_n < \ell nA$, CONTINUE DEFERRED DECISION

$T_n \geq \ell nA$, TERMINATE, ACCEPT H_1

$T_n \leq \ell nB$, TERMINATE, ACCEPT H_0

$$ASN = \overline{n} = \frac{L(h)\,\ell nB + [1 - L(h)]\,\ell nA}{E[T_i]}, \quad h \neq 0$$

$$\overline{n} = \frac{L(o)\,(\ell nB)^2 + [1 - L(o)]\,(\ell nA)^2}{E[T_i^2]}, \quad h = 0$$

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Viewgraph 5

The ASN is defined as the average number of samples (pings) needed to terminate the sequential procedure. The equation for ASN (n) is shown here for $h \neq 0$ and for $h=0$.

DETECTOR

$$T_N = \sum^{N} T_i' \quad ,$$

$$\lim_{N \to \infty} Pr_q \{[T_N - E_q (T_N)]/\sigma_q (T_N)\} \to N(0, 1)$$

FIXED SAMPLE

$$N = \{\Phi^{-1}(1-\alpha) - \Phi^{-1}(\beta)\}^2/d$$

SEQUENTIAL

$$n = \inf \{n : T_N \not\in (b,a)\}$$

$$E(n|\delta) = \begin{cases} (-2/hd)\,[b\,L(\delta) + a\,(1-L(\delta))], & h \neq 0 \\ -ab/d & , h = 0 \end{cases}$$

$$h = 1 - 2\delta/\delta_1 \ ; \ d = [E(T_i'|H_1) - E(T_i'|H_0)]^2 / Var(T_i'|H_0)$$

RELATIVE EFFICIENCY

$$RE = N/E(n|\delta) \ ; \ h = \pm 1, h = 0$$

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Viewgraph 6

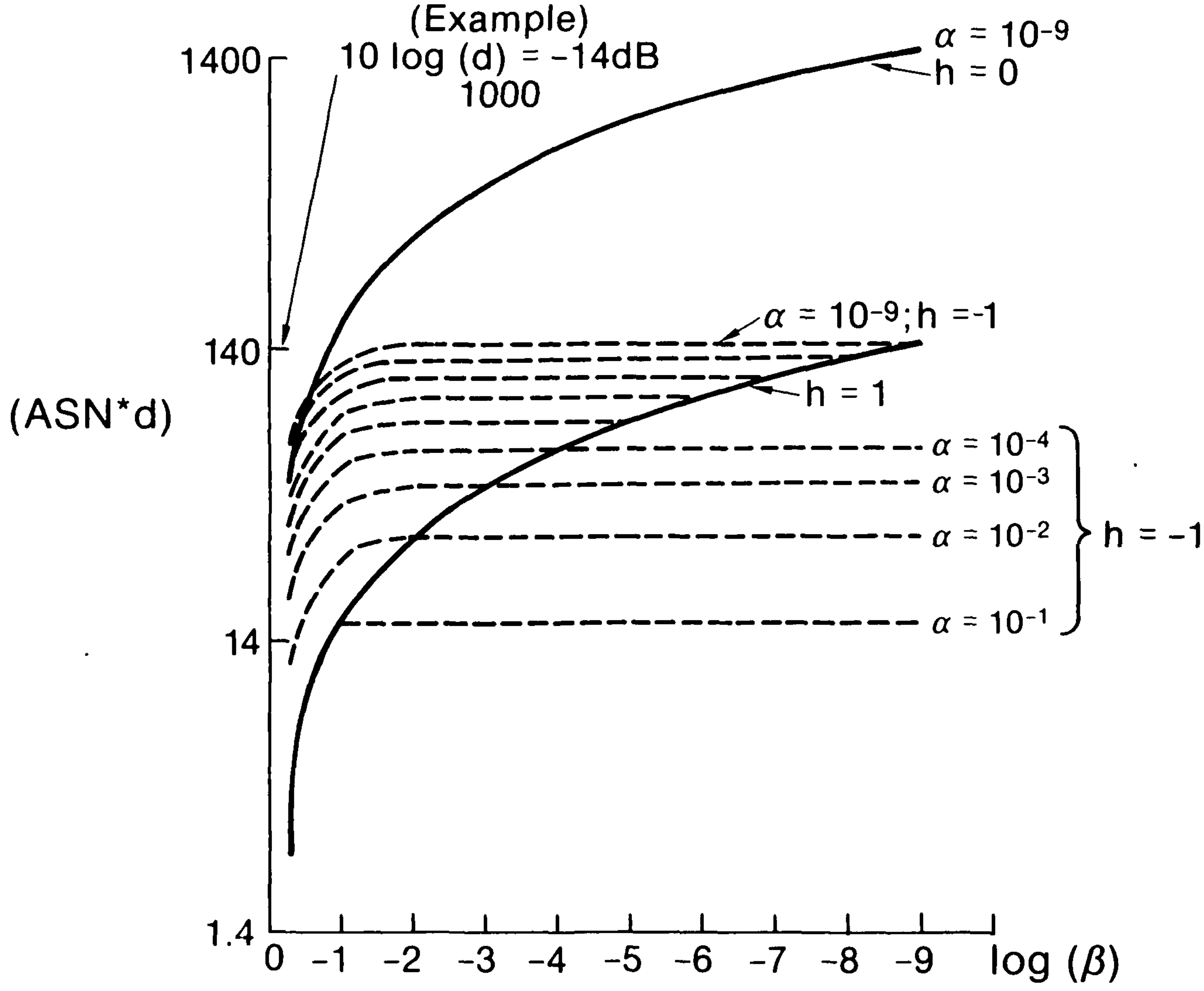
The next 6 figures show asymptotic results. Since it is difficult to obtain general design results for a loglikelihood ratio receiver, because it depends on knowledge of the probability density functions, asymptotic performance results are very useful. Here we assume that the samples (pings) are statistically independent and that the number of samples are sufficiently large to assure that the loglikelihood ratio approaches a Gaussian process. In this way we can compare the performance of a fixed sample detector and a sequential detector using the relative efficiency as a performance measure. However, non-asymptotic results, which will be given later, correspond with these results very well.

The relative efficiency is defined as the ratio

$$RE = N/E(n)$$

where, N is the number of samples (pings) required by a fixed sample detector to achieve the desired α and β. Whereas, E(n) is the average number of samples of the sequential detector under the same desired α and β.

Average Sample Number (ASN)



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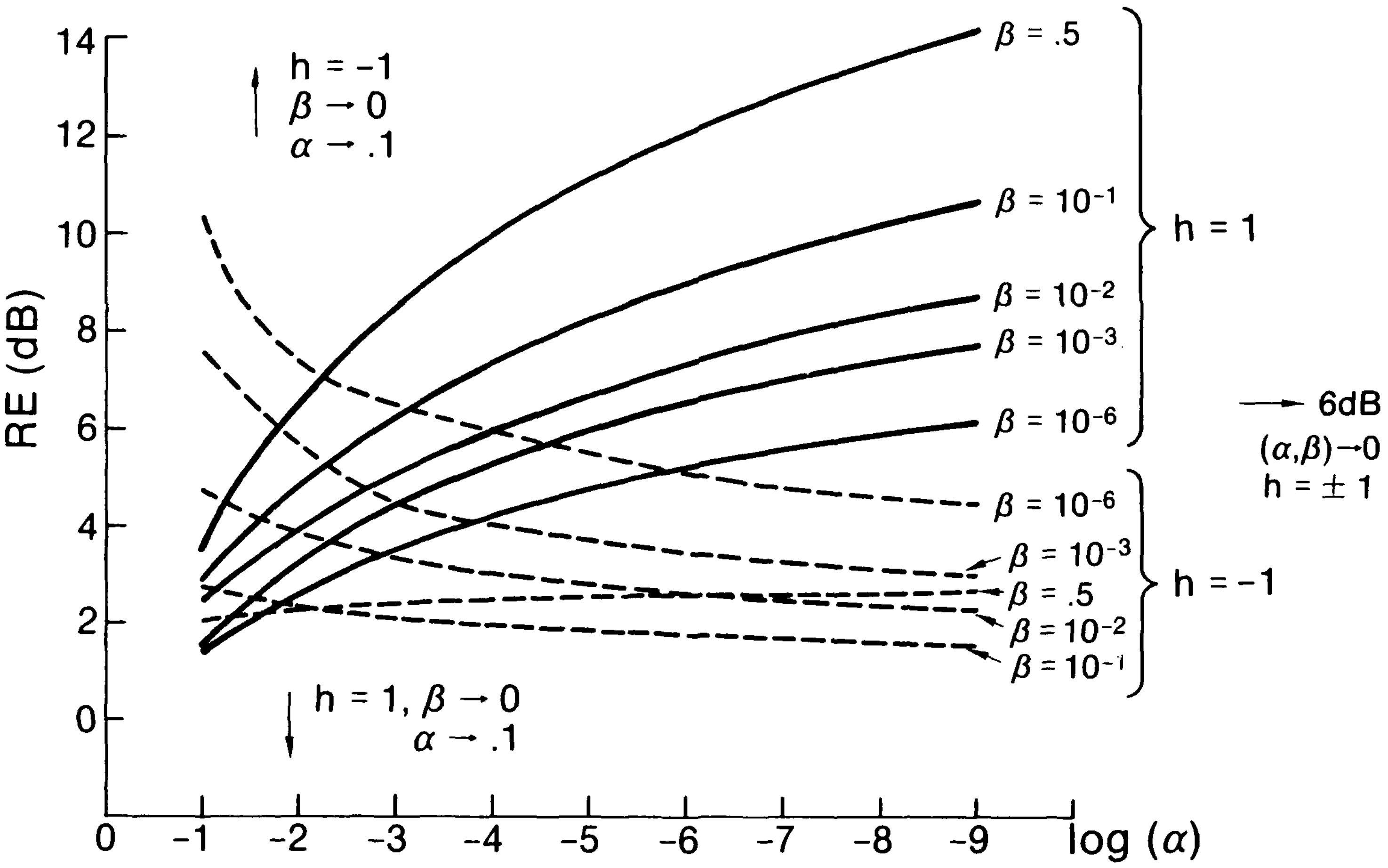
Viewgraph 7

The ASN is defined as the average number of pings needed to make a decision for prescribed α and β.

The figure gives design curves as a function of α and β. To generalize the results the ASN has been multiplied by d, the signal-to-noise ratio. Three conditions are plotted in the figure, $h = \pm 1$ and $h = 0$.

Relative Efficiency at h = ± 1

$$RE = -(1/2)\, h(\delta)\, \frac{[\Phi^{-1}(1-\alpha) - \Phi^{-1}(\beta)]^2}{b\, L(\delta) + a\,(1-L(\delta))}$$



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Viewgraph 8

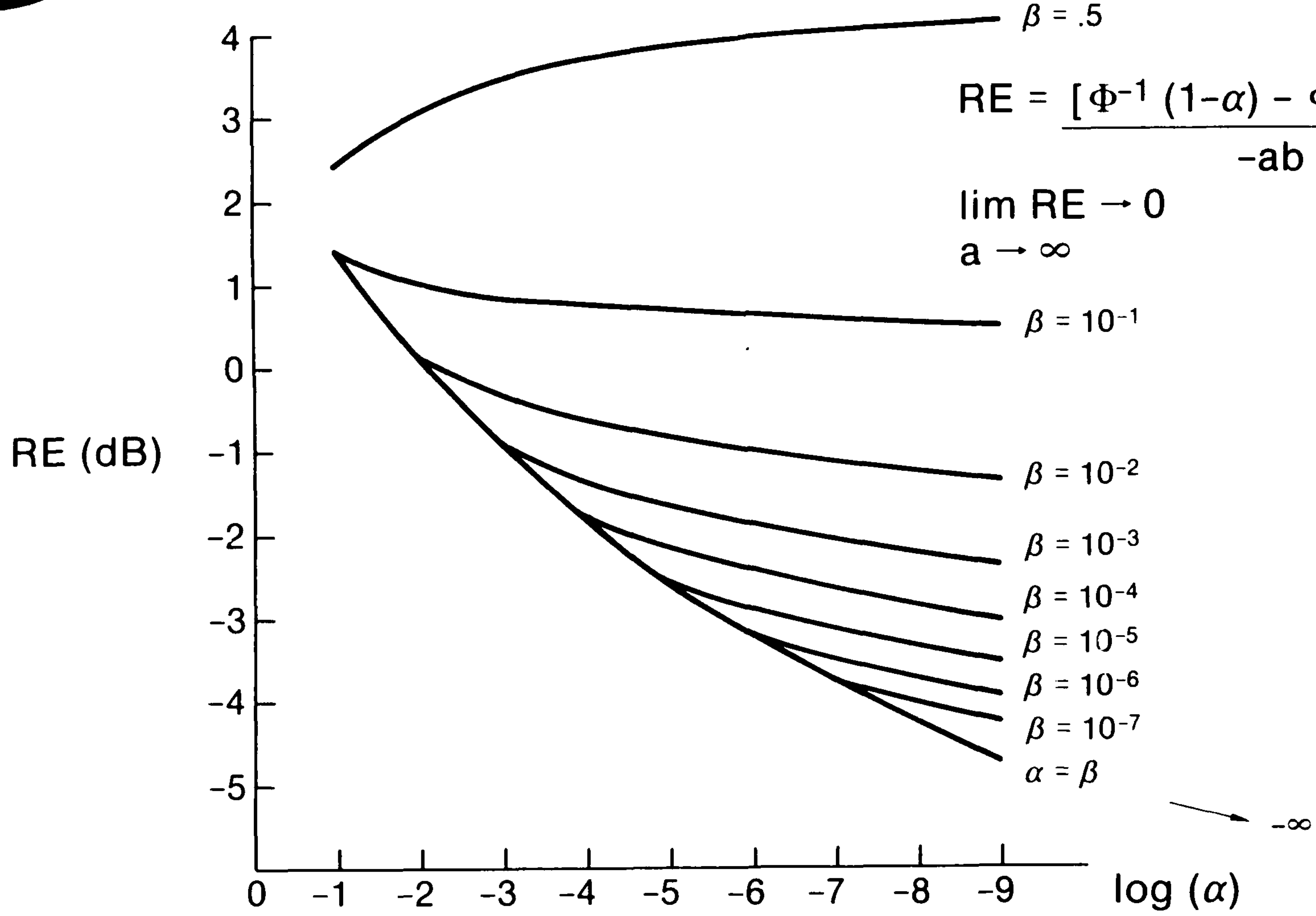
In this figure the relative efficiency (RE) is plotted for $h = \pm 1$. As α and β approach zero the RE approached 6 dB. This means that the fixed sample detector requires 4 times as many pings as does the sequential detector to make a decision.

At $\alpha = 10^{-8}$ and $\beta = 10^{-1}$ then the RE is 10 dB at $h = 1$, and 2 dB at $h = -1$. These results are very significant and clearly show the benefit of sequential detection.

Relative Efficiency at $\delta = \delta_c$

$$RE = \frac{[\Phi^{-1}(1-\alpha) - \Phi^{-1}(\beta)]^2}{-ab}$$

$$\lim_{a \to \infty} RE \to 0$$



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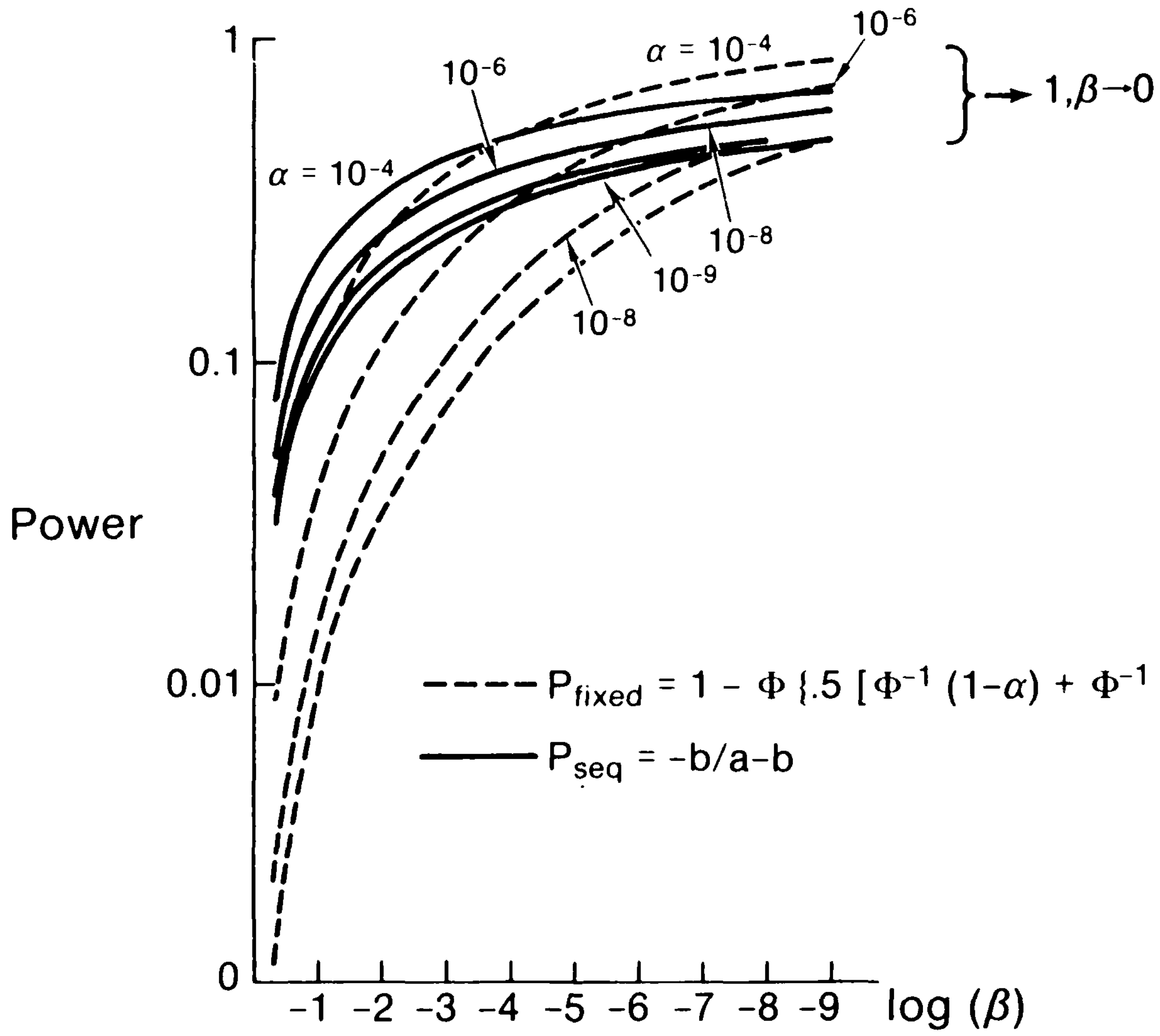
Viewgraph 9

This figure shows the RE at $h = 0$ or the critical point. If $\alpha = 10^{-8}$ and $\beta = 10^{-1}$ the RE is still greater than one.

Power Comparison at $\delta = \delta_c$



$P_{fixed} = 1 - \Phi \{.5 [\Phi^{-1} (1-\alpha) + \Phi^{-1} (\beta)]\}$

$P_{seq} = -b/a-b$

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Viewgraph 10

It is also important to know what the probability of detection (power) is at $h = 0$. This figure compares the power of the sequential detector with the power of the fixed sample detector at $h = 0$.

TRUNCATION

MODIFIED THRESHOLDS

$$b\,G(n) < T_n < a\,G(n)\,,$$

$$G(n) = (1 - n/N_T)\ ,\ o < G \leq 1\ ,\ n < N_T$$

OC FUNCTION

$$L(\delta) = E_a\,[\exp\,(aGh) - 1]/\{E_a\,[\exp\,(aGh)] - E_b\,[\exp\,(bGh)]\}$$

$$L(\delta_c) = a\,E_a\,(G)/\{a\,E_a\,(G) - b\,E_b\,(G)\}$$

ASN

$$E_T\,(n|\delta) = \begin{cases} (-2/hd)\,[a\,E_a\,(G)\,(1 - L(\delta)) + b\,E_b\,(G)\,L\,(\delta)], & h \neq 0 \\ (-ab/d)\left[\dfrac{a\,E_a\,(G^2)\,E_b\,(G) - b\,E_b\,(G^2)\,E_a\,(G)}{a\,E_a\,(G) - b\,E_b\,(G)}\right], & h = 0 \end{cases}$$

RESULTS (APPROXIMATE)

$$\left.\begin{aligned} &E_T(n) \geq E(n)/(1 + E(n)/N_T) \leq E(n) \\ &\alpha_T \sim \alpha\,[1 + a\,E(n)/(N_T + E(n))] \end{aligned}\right\}\ h = -1$$

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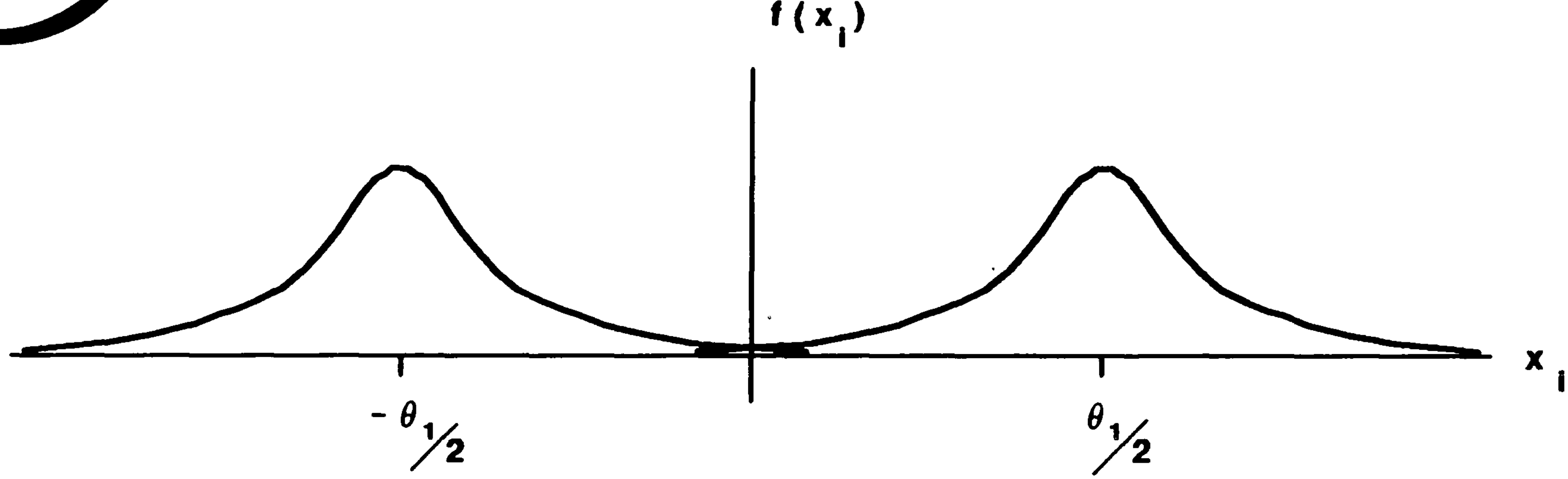
Viewgraph 11

In a previous figure truncating the sequential detector to force a decision at some point in time was discussed. Here the thresholds are modified by a function G(n). This is a very general approach to the forced decision boundary problem. The performance measures are given in this figure for the modified thresholds. For the special case shown truncation reduces the ASN, but on the other hand the error rates increase. The derived mathematical relationship can now be used to trade-off the number of pings with the increased error rates. These results also hold in general.



$T_i = \theta_1 x_i$, $E[T_i \mid H_0] = -\theta_1^2/2$; $E[T_i \mid H_1] = \theta_1^2/2$

$T_n = \theta_i \sum_{i=1}^{n} x_i$, $b < T_n < a$

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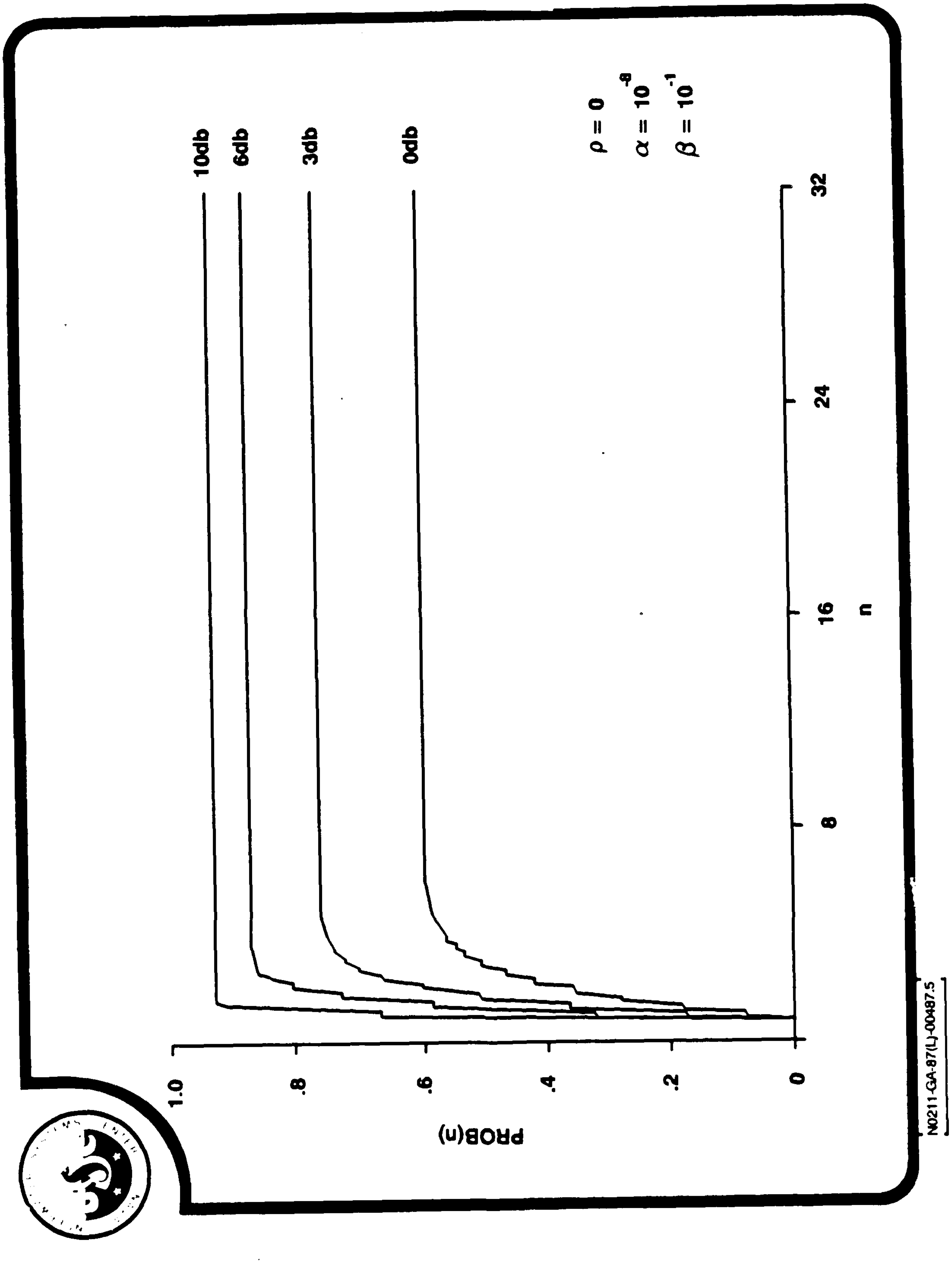
Viewgraph 12

This figure shows a one-dimensional Gaussian example. Here the matched filter output is a unit variance Gaussian process. The mean value is $\Theta_1/2$ under H_1 and $-\Theta_1/2$ under H_0. The loglikelihood ratio is employed to obtain T_n.

In the next two figures the results for this example are given. But the data is first quantized into two levels. This is appropriate since information given to operators on displays are quantized and in general computers require quantized data.

VIEWGRAPH 13



Viewgraph 13

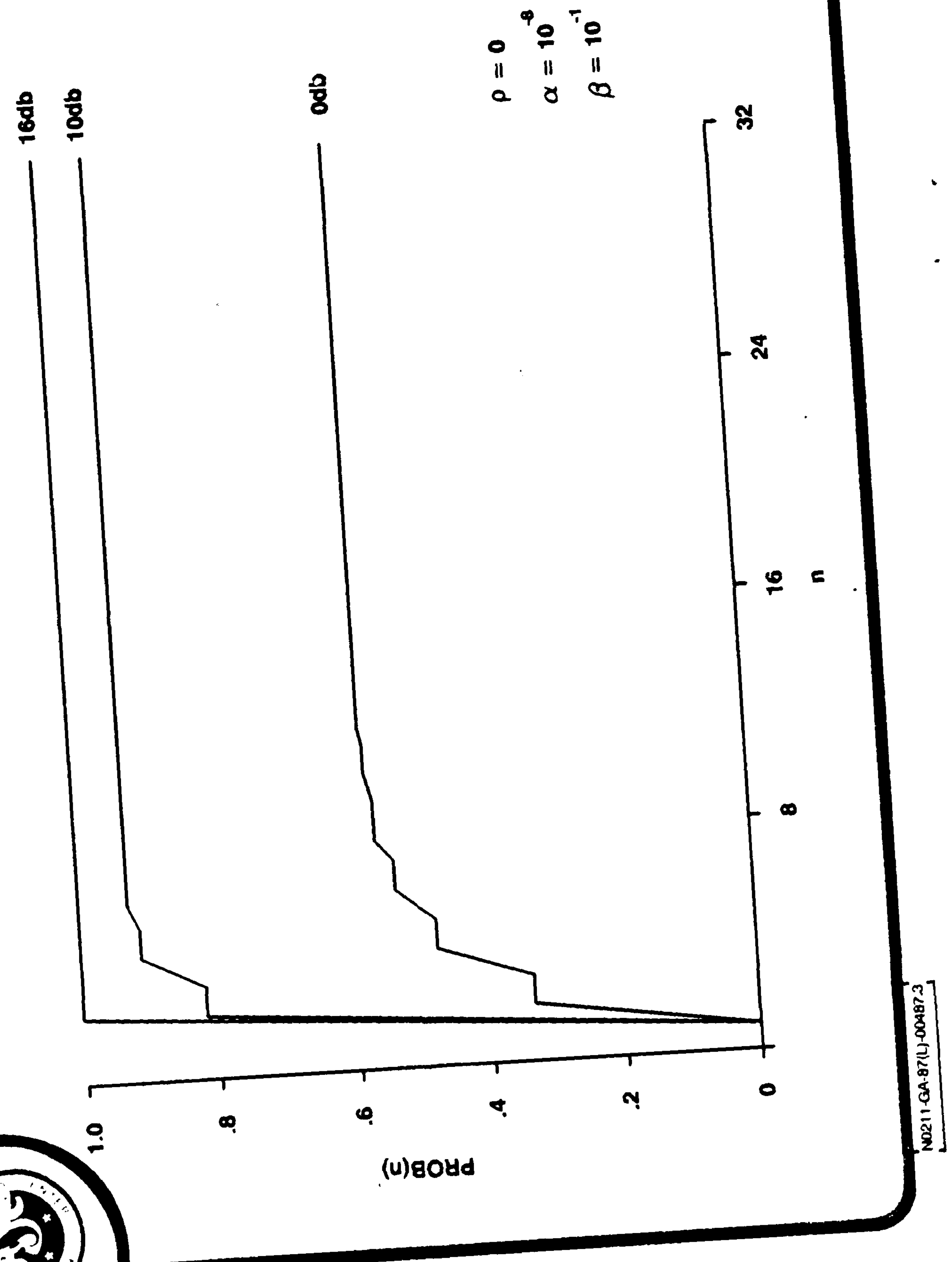
The design parameters for the sequential detector were $\alpha = 10^{-8}$ and $\beta = 10^{-1}$; whereas the design signal-to-noise (SNR) was 10 dB.

The figure gives the probability of terminating the sequential detector with the acceptance of H_1 as a function of n. The plot is therefore the cumulative distribution function for n.

At 10 dB SNR Prob(n) approaches .9 as n increases. Notice that there is a probability of .1 of terminating the test with the acceptance of H_0, but this is the desired error rate β.

If the true SNR is less than the design SNR then Prob(n) < .9. This is a general result which holds for all sequential detectors.

VIEWGRAPH 14

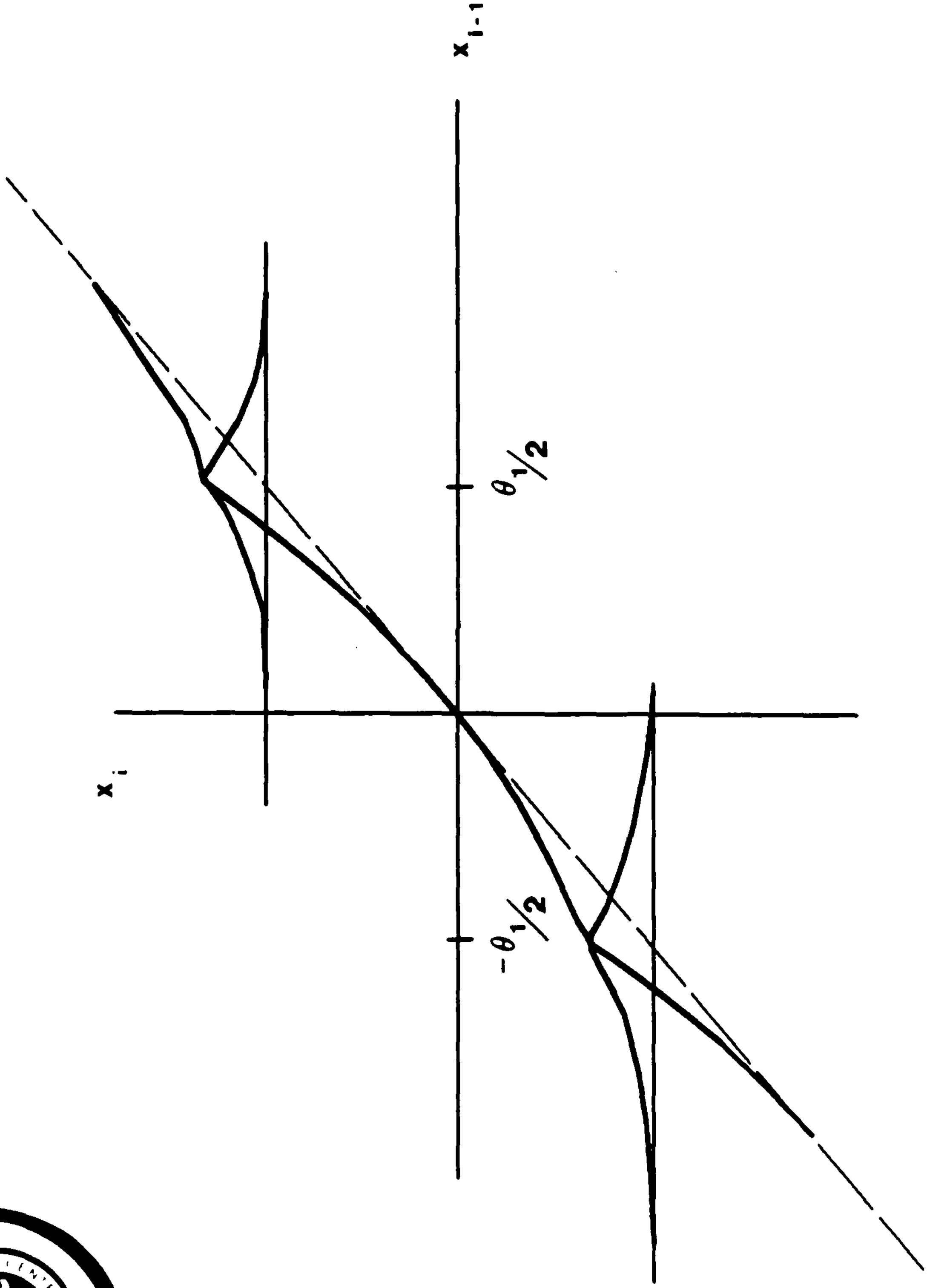


Viewgraph 14

In this figure the design SNR was 16 dB. Now Prob(n) approaches .99 even though α and β are the same as before. The reason this happens is, because, the excess over the boundaries cannot be neglected for high SNR.

As the true SNR decreases from design conditions Prob(n) also decreases.

VIEWGRAPH 15



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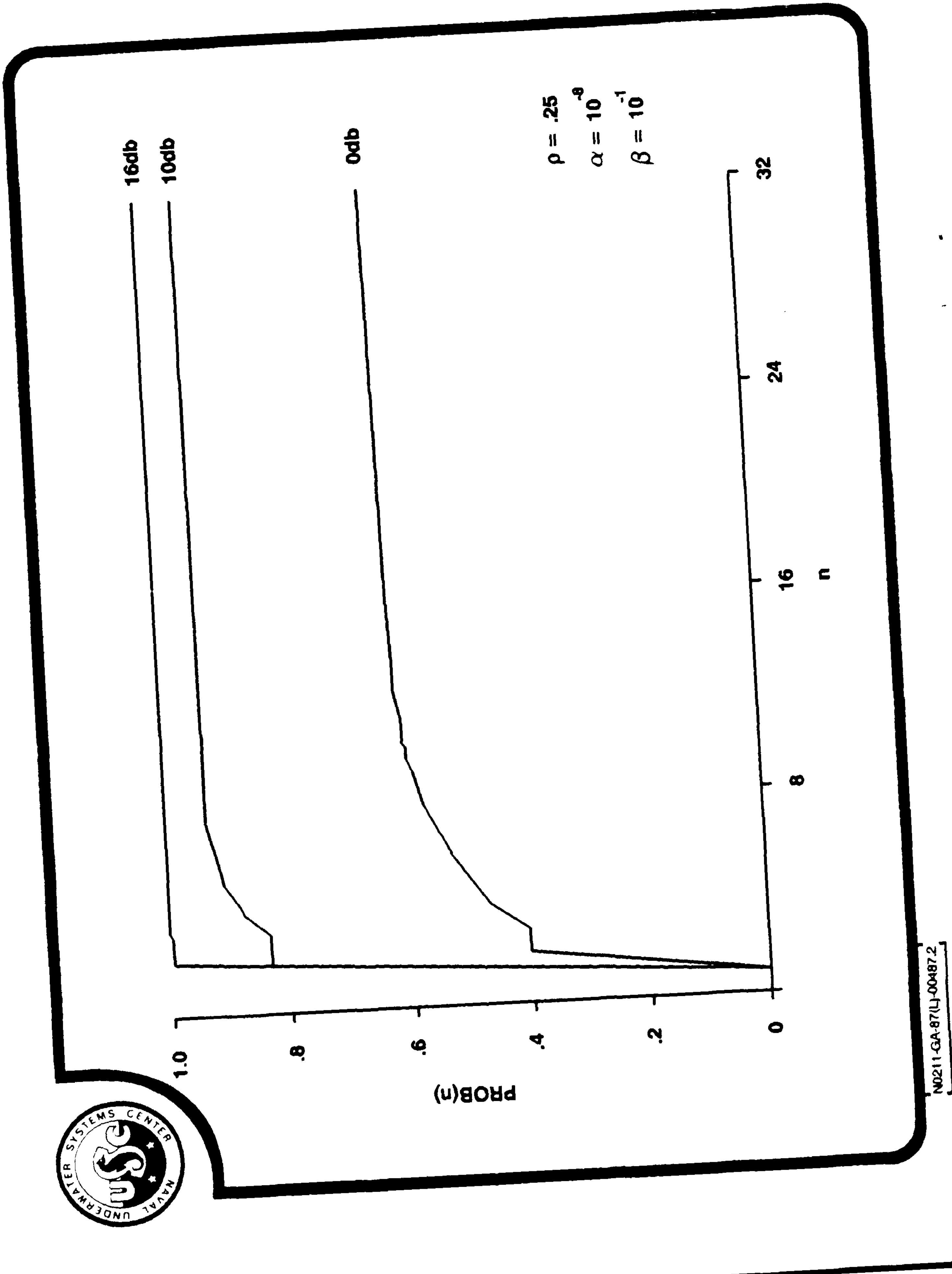
Viewgraph 15

Now the two-dimensional Gaussian example will be considered. In this case we are assuming that the matched filter output is correlated with the previous ping output. This is called a Markov process. The output of a two level quantizer will be again considered in the following data examples, but now, instead of two regions as in the one-dimensional case, there are 4 quadrants.

VIEWGRAPH 16

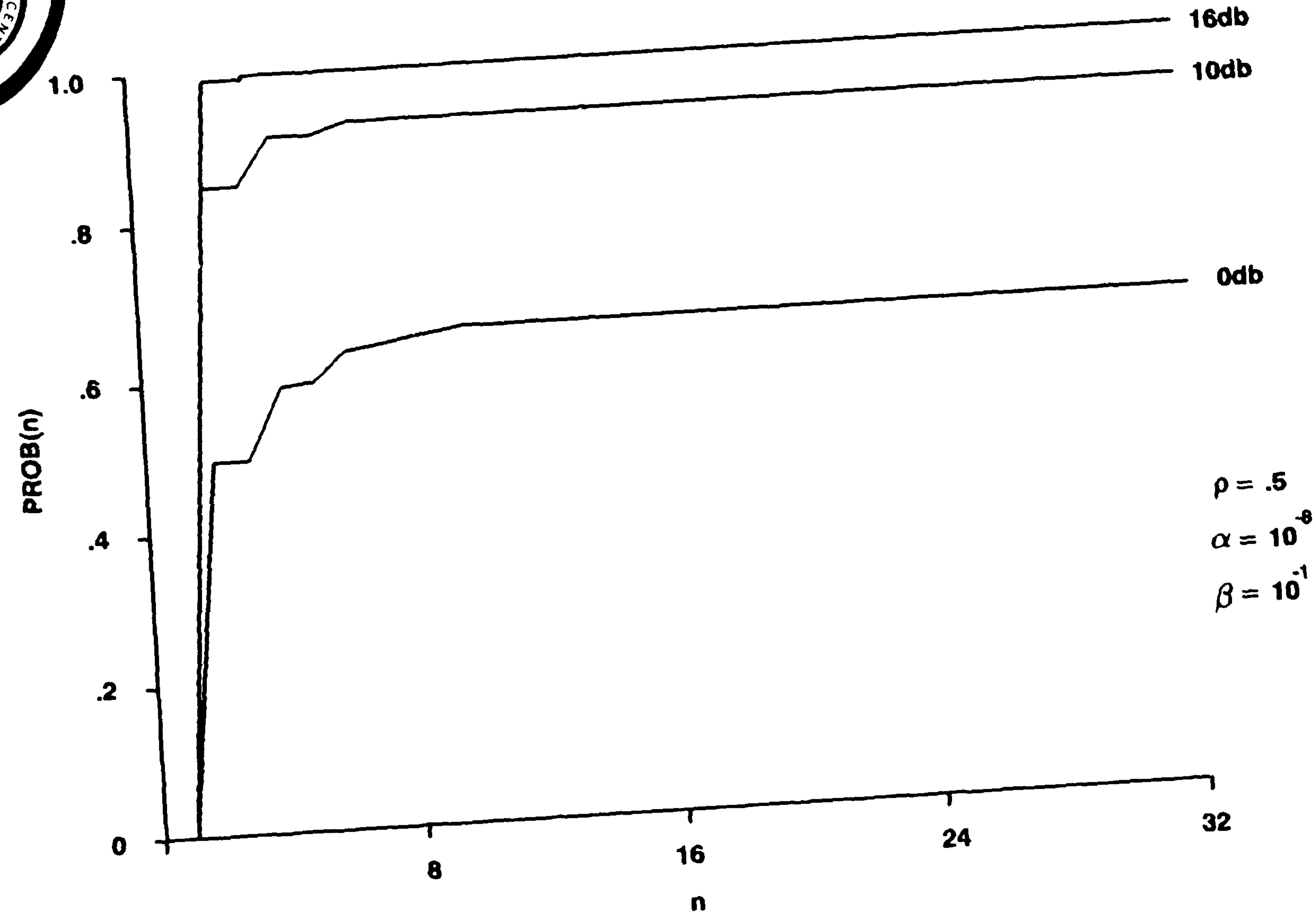


Viewgraph 16, 17, and 18

The next three figures show the results for the two-dimensional Gaussian example. Only the correlation coefficients were changed in each figure. They are .25, .5, and .75, respectively for the next three figures.

The previous figure and the next three figures are for the same high SNR case of 16 dB. However, as the correlation coefficient increases the performance improves for the off design SNR cases. This result may be significant because it represents a method to improve active sonar performance. However, the receiver must be designed from the likelihood ratio in order to achieve improvements. This is true because the likelihood ratio incorporates correlation to achieve an optimum receiver.

As far as the figures are concerned, correlation reduces the false dismissal rates and, thereby, increases detection. Inspection of the likelihood ratio, on the other hand, reveals that correlation shifts its weighting structure to favor detection when correlated data are present. Whereas, potential tracks produced by uncorrelated noise data are quickly rejected.



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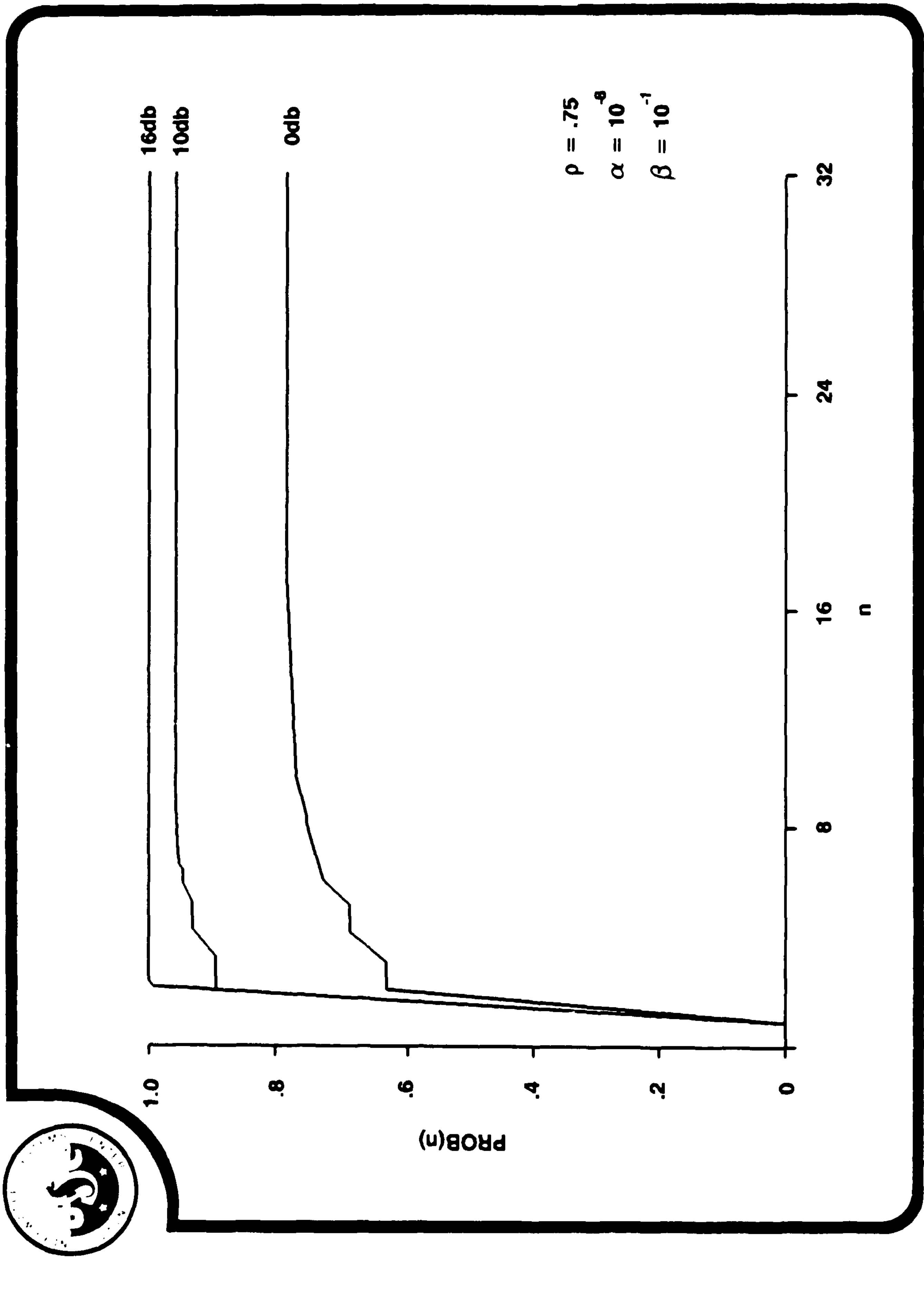
VIEWGRAPH 18



Rayleigh Fluctuating Target

$$f(x|H_1) = \frac{x}{1+s} \exp(-x^2/2(1+s))\, u(x)$$

$$f(x|H_0) = x\, E(-x^2/2)\, u(x)$$

WHERE, $\sigma^2 = 1+s$

$$T_i = -\ell n(1+s_1) + \left(\frac{s_1}{1+s_1}\right) x_i^2/2 \; ; \quad E[T_i] = -\ell n(1+s_1) + s_1\left(\frac{1+s}{1+s_1}\right)$$

(WEAK SIGNAL CASE)

$$E[T_i] = \frac{-s_1^2}{2} + s s_1$$

EXAMPLE:

$$ASN = \overline{n} = \frac{L(h)b + (1 - L(h))a}{E[T_i]} \; ; \quad L(1) = 1 - \alpha,\ L(-1) = \beta$$

s_1 = 16dB, $\overline{n}_0$ = .84, $\overline{n}_1$ = .5

s_1 = 10dB, $\overline{n}_0$ = 1.54, $\overline{n}_1$ = 2.14

s_1 = 6dB, $\overline{n}_0$ = 2.84, $\overline{n}_1$ = 6.8

s_1 = 3dB, $\overline{n}_0$ = 5.3 , $\overline{n}_1$ = 18

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Viewgraph 19

The next example is for the Rayleigh fluctuating target. This model is currently employed in active sonar. Therefore, a complete formulation of the sequential detector using Rayleigh statistics are given.

Here the envelope of the matched filter output is represented by x. The probability density functions under H_0 (noise only) and H_1 (signal and noise) are shown. The loglikelihood ratio from these two densities is given by T_i. This gives the optimum receiver for the Rayleigh fluctuating target model. From this information and the thresholds the ASN can be computed. Several cases are shown. For the high SNR case (S_1 = 16 dB), Wald's formulation does not give an accurate prediction. This is due to the assumption of neglecting the excess over the boundaries. For lower SNR Wald's formulation is very accurate. As SNR decreases more pings are required to detect the target for the prescribed error rates. Notice how the number of pings required falls off as SNR decreases. This is a nonlinear relationship. For only a 3 dB increase in SNR there is a significant decrease in the number of pings required to detect the target.

$$\int_0^\infty \left[\frac{1}{1+s_1} e^{\frac{x^2}{2}\left(\frac{s_1}{1+s_1}\right)} \right]^{h(s,\, s_1)} \frac{x}{1+s} e^{-\frac{x^2}{2(1+s)}} \, dx = 1$$

SMALL SIGNAL APPROXIMATION

$$\boxed{h = 1 - 2s / s_1}$$

$$L(h) = (e^{ah} - 1) / (e^{ah} - e^{bh})$$

h	$L(h)$
1	$1 - \alpha$
.25	.995
.01	.9
0	.888
$-.1$	.765
-1	$.1 = \beta$

$a = 18.3$, $b = -2.3$

$\alpha = 10^{-8}$

$\beta = 10^{-1}$

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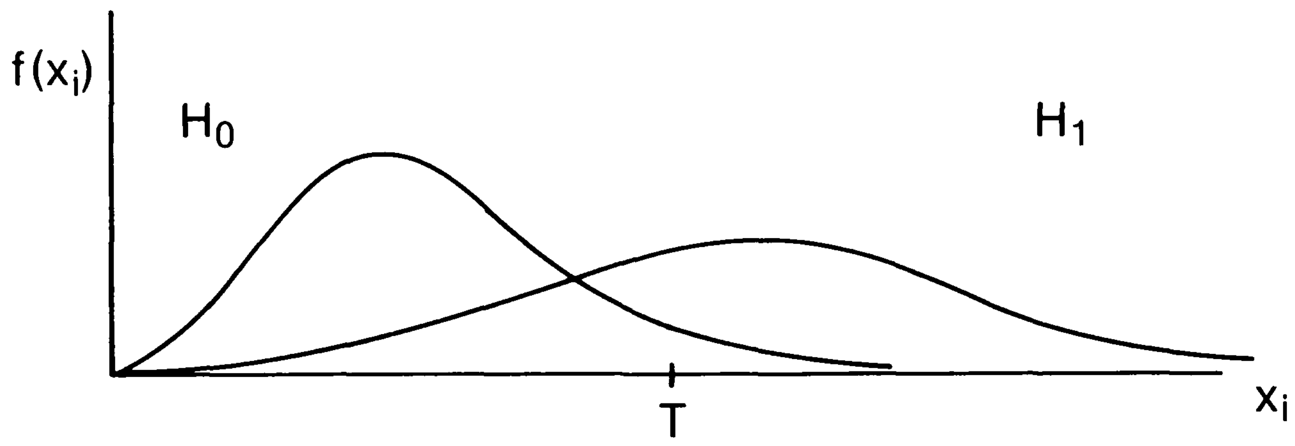
Viewgraph 20

In the previous figure the ASN for the Rayleigh fluctuating target was obtained. Here the operating characteristic function is evaluated for the Rayleigh fluctuating target.

The objective is to solve the integral equation for the parameter h. This integral can be solved. The derived parametric relationship for h, however, is nonlinear with respect with S and S_1. The small signal approximation is also given. This relationship agrees with the generalized asymptotic results given previously.

Once h is obtained the operating characteristic function can be evaluated given the thresholds. As h varies from 1 to -1, L(h) varies from $1 - \alpha$ to β.
Some specific results are shown.



$$P_{01} = \text{PROB}\,[x_i < T \mid H_0]$$

$$P_{02} = \text{PROB}\,[x_i > T \mid H_0]$$

$$P_{12} = \text{PROB}\,[x_i > T \mid H_1]$$

$$P_{11} = \text{PROB}\,[x_i < T \mid H_1]$$

$$b_1 = \ell n \left(\frac{P_{11}}{P_{01}}\right); \quad b_2 = \ell n \left(\frac{P_{12}}{P_{02}}\right)$$

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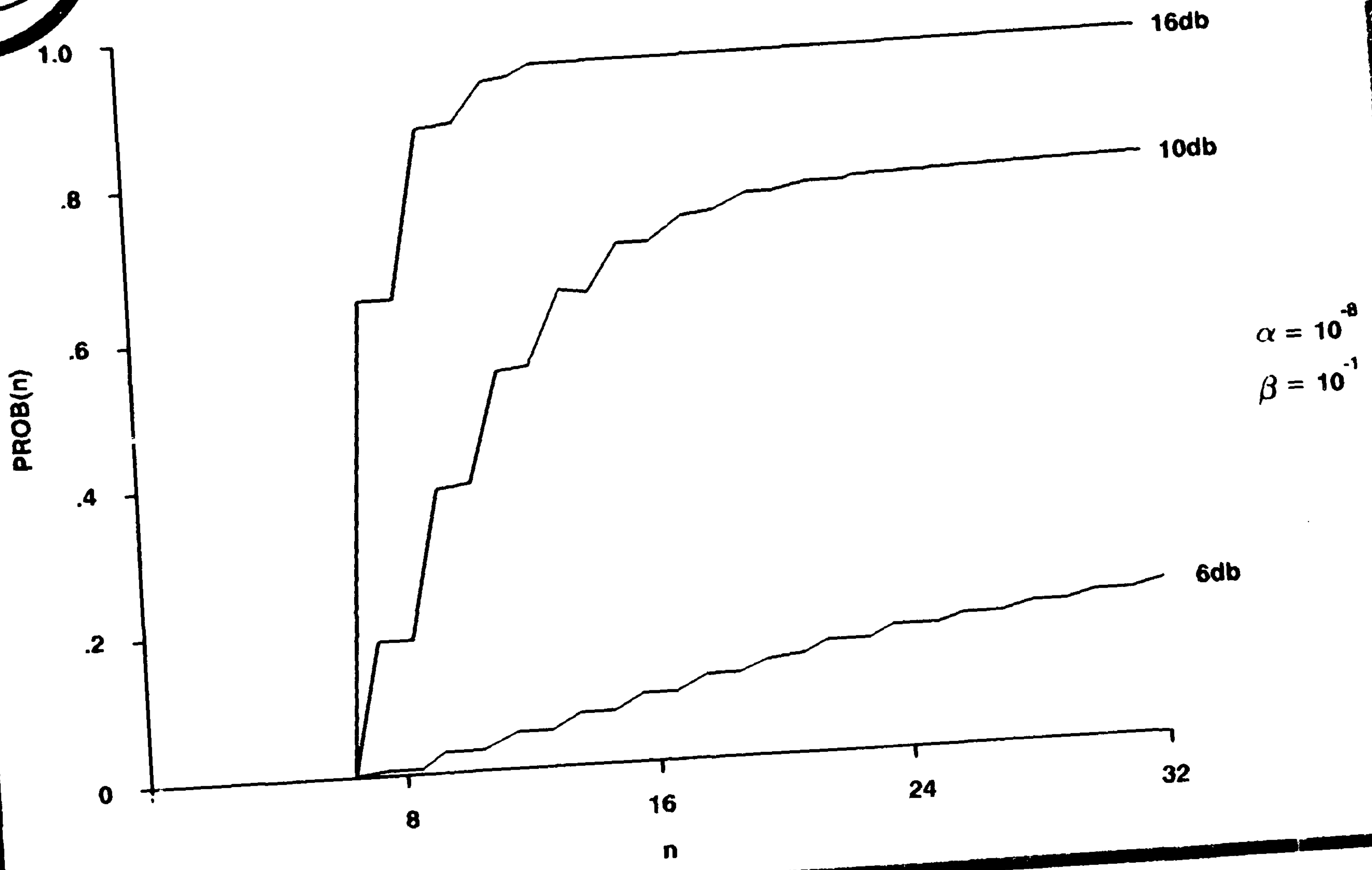
Viewgraph 21

In this example the data at the matched filter is again quantized into two regions. The regions are separated by T in the figure. When the data from a ping falls into one of the regions a value is assigned based on the probability of being in this region under H_0 and H_1. These values are denoted by b_1 and b_2 in the figure.

The next figure shows the results of the two-level quantizer.

RAYLEIGH



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Viewgraph 22

The results of the two-level quantizer example is shown in this figure. The design SNR is 16 dB and α is 10^{-8} and β is 10^{-1} as before. We see that for 16 dB SNR the sequential detector will achieve its design conditions. However, as the SNR decreases from the design SNR the performance falls off and the desired false dismissal rate is not achieved.

CONCLUSIONS

- SEQUENTIAL DETECTORS MINIMIZE AVERAGE DECISION TIME
- UTILIZE KNOWLEDGE OF PROBABILITY DENSITY FUNCTIONS TO FORM AN OPTIMUM DETECTOR BASED ON THE LIKELIHOOD RATIO
- SENSITIVE TO PARAMETER AND PROBABILITY DENSITY MISMATCH

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Viewgraph 23

Automated detection and tracking systems which utilize sequential analysis are assured of minimizing their average decision time. This is accomplished by incorporating knowledge of the underlying probability density functions based on the likelihood ratio. The resulting automated system acts much like a human operator in that the sequential detector defers a decision until a high level of confidence in the target is obtained. But unlike an operator target tracks which accumulate low levels of confidence are dropped from computer memory. This is an important requirement because it allows additional potential targets to be tracked.

The automated system, however, is sensitive to parameter and probability density function mismatch. There are several methods to overcome these disadvantages. These methods will be discussed in future reports.

References

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